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Key Points:
- First direct measurement of the depth of a Titan sea
- First determination of the nearly pure methane-ethane Ligeia Mare composition
- Determination of the total volume of Ligeia Mare

Supporting Information:
- Readme
- Auxiliary material

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The bathymetry of a Titan sea

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Abstract We construct the depth profile—the bathymetry—of Titan's large sea Ligeia Mare from Cassini RADAR data collected during the 23 May 2013 (T91) nadir-looking altimetry flyby. We find the greatest depth to be about 160 m and a seabed slope that is gentler toward the northern shore, consistent with previously imaged shoreline morphologies. Low radio signal attenuation through the sea demonstrates that the liquid, for which we determine a loss tangent of $3 \pm 1 \cdot 10^{-5}$, is remarkably transparent, requiring a nearly pure methane-ethane composition, and further that microwave absorbing hydrocarbons, nitriles, and suspended particles be limited to less than the order of 0.1% of the liquid volume. Presence of nitrogen in the ethane-methane sea, expected based on its solubility and dominance in the atmosphere, is consistent with the low attenuation, but that of substantial dissolved polar species or suspended scatterers is not.

1. Introduction

Hundreds of lakes and seas have been imaged on Saturn's large moon Titan [*Stofan et al*., 2007; *Hayes et al*., 2008] and assumed on indirect inference to contain ethane and methane [*Elachi et al*., 2004; *Lunine and Lorenz*, 2009; *Brown et al*., 2008]. During Cassini flybys denoted T25 (22 February 2007), T28 (10 April 2007), T29 (26 April 2007), T64 (28 December 2009), T92 (10 July 2013), and T95 (14 October 2013) the Cassini RADAR mapped Ligeia Mare, located at 79°N latitude and 250°W longitude and spanning an area of 126,000 km^2. Ligeia Mare's surface area is second only to that of Kraken Mare; the International Astronomical Union has given these and one other large feature the designation of "mare", or sea, rather than a "lacus", or lake. Cassini RADAR images of Ligeia Mare show a very dark central region surrounded by increasing radar brightness near the edges. These were suggested to be reflections from a shallow bottom [*Stofan et al*., 2007]. The capability of radar to penetrate materials such as liquid hydrocarbons is mainly the result of the low loss tangent of those materials at the instrumental wavelength (2.17 cm) and under probable Titan surface conditions. Laboratory measurements of the dielectric properties of liquid nitrogen [*Smith et al*., 1991] and liquid alkanes [*Dagg and Reesor*, 1972; *Gelsthorpe and Bennett*, 1978; *Smith et al*., 1991] imply that the Cassini RADAR could probe depths of up to few hundred meters through Titan's lakes and seas in a mode in which the radar is pointed straight downward, rather than to the side when used as imager.

During the T91 Titan flyby (23 May 2013), the Cassini RADAR observed Ligeia Mare in the nadir direction at an altitude of 1600 km and collected data along a nearly 300 km track. The relatively low flyby altitude, combined with data processing to suppress the lateral lobes of the strong surface reflection and enhance spatial resolution, made possible the detection of subsurface echoes reflected from the bottom of the sea. The processing revealed the bottom reflection along the entire track across Ligeia and thereby we were able to construct the first-ever bathymetry sounding of an extraterrestrial sea.

2. Method

We used T91 Cassini RADAR altimeter echoes reflected from the bottom of Ligeia Mare in order to derive the depth profile and the loss tangent of the liquid hydrocarbons filling the basin. We analyzed the so-called

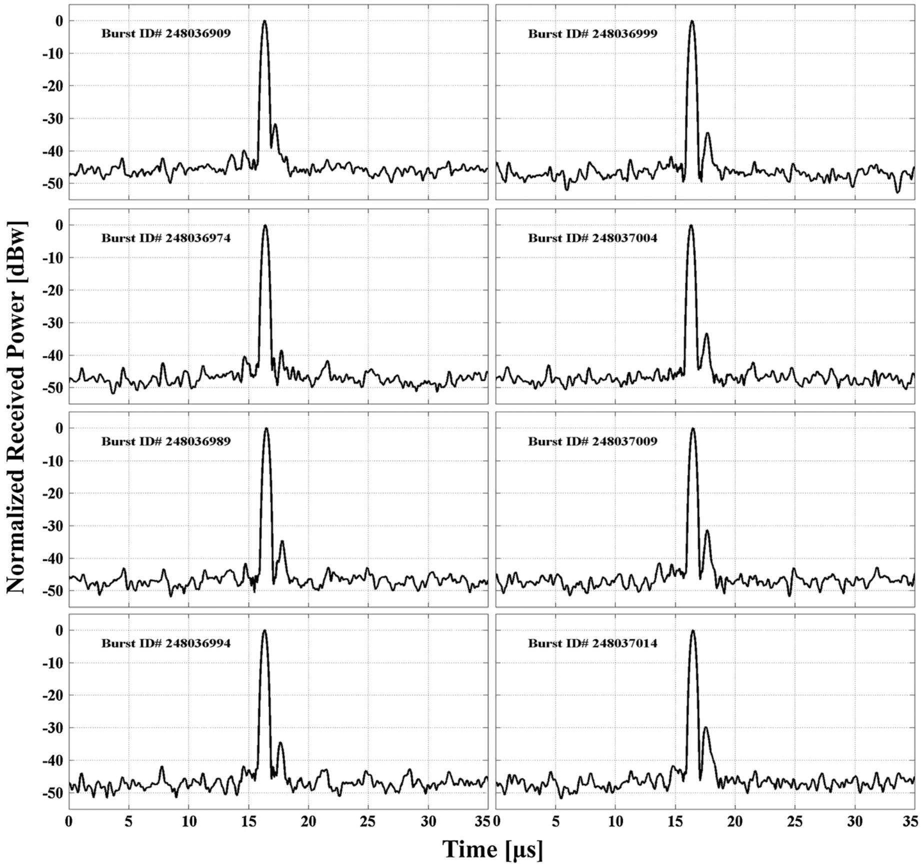

Figure 1. T91 Cassini altimeter pulses acquired over Ligeia Mare, Kaiser-Bessel taper function, and incoherent averaging were used to process echoes for data analysis. The first strong echo represents the reflection from the sea surface followed by a second weak reflection from the seabed.

"Cassini processing of altimetric data (CPAD) products" [*Alberti et al*., 2007], which are derived from range compression, Taylor tapering and incoherent averaging. Because the standard processing reveals only the surface echoes followed by side lobes generated by the first strong reflection, we reprocessed the T91 data using a custom taper function (the Kaiser-Bessel and Blackman window, *Harris*, 1978) to better reduce side lobes of the first strong reflection by over 60 dB (see section 2 in the supporting information). Incoherent averaging of the multiple pulses contained in each transmitted burst then revealed clearly reflected echoes from the bottom of the sea with an signal-to-noise ratio of up to 15 dB, as seen in Figure 1 (see also section 3 in the supporting information).

We applied three more steps of signal processing in order to enhance spatial resolution and subsurface echoes detection. First, we applied a superresolution maximum entropy method (MEM) [*Moore et al*., 1997; *Herring*, 1980] to improve the nominal 35 m of range resolution of Cassini Radar [*Zebker et al*., 2009]. We extended the 4.25 MHz received bandwidth up to 9 MHz by extrapolating part of the spectrum using Burg algorithm [*Burg*, 1975] (see section 1 in the supporting information). In doing that, we sharpened the radar range resolution, indeed the capability to distinguish and localize surface-subsurface maxima peaks values (Figures 2a and 2b).

Second, we applied the Kaiser-Bessel window to control the shape of the filter. We adapted the window in order to improve echo peak separation over the shallower portion of the sea and ensure that the side lobes level of the surface signal be at least 10 dB weaker with respect to the subsurface second peak amplitude.

Third, in order to improve the subsurface detection, we analyzed all the bursts in the range—Doppler domain and averaged the portion of the spectrum (five filters) where the subsurface signal is expected to appear.

The image generated as the result of this processing is shown in Figure 3.

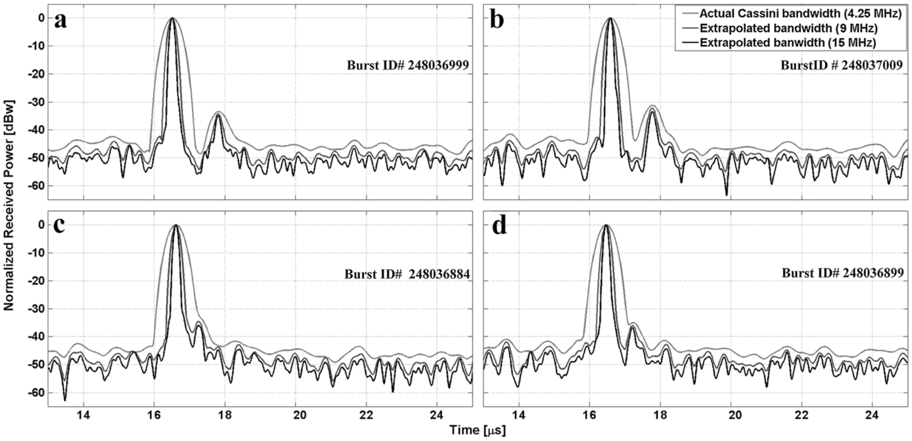

Figure 2. MEM method via Burg algorithm for superresolution techniques applied to Cassini T91 altimeter data. The superresolution allows to distinguish surface-subsurface peaks under the nominal radar range resolution (c, d) and improve the time distance measurements of surface-subsurface peaks (a, b).

The seafloor complex morphology observed at the shorelines from images, together with multiple bounces at the interfaces of the shallower depths causes multiple peaks in the radar echoes and makes it a challenge to distinguish the first surface reflection from the second one. Thus, the first six echoes and the last one were extracted and processed with the optimal Burg extrapolation and Kaiser-Bessel beta parameter which allows for the best separation of the echoes from the seafloor and the surface. This processing allowed tracking the position of partially merged surface-subsurface peaks ranging up to 15–20 m from each other. In this region the surface and subsurface echoes were merged when standard processing was applied (Figures 2a and 2b).

The tracking algorithm localizes the position of the two maxima signals amplitudes (surface and subsurface) and verifies that the second peak (subsurface) is not preceded by other peaks (i.e., peaks at least −1 dB below

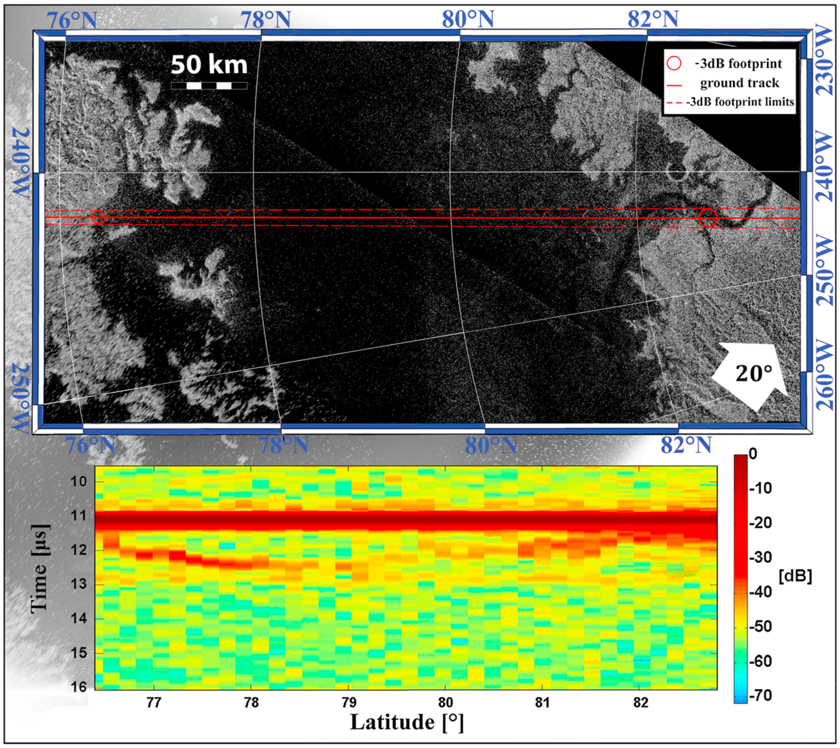

Figure 3. The upper image shows the T29 SAR image of Ligeia Mare with the superimposed altimetry T91 track. Red circles indicate start and stop altimetry track. The image in the bottom shows the radargram obtained by processing T91 data.

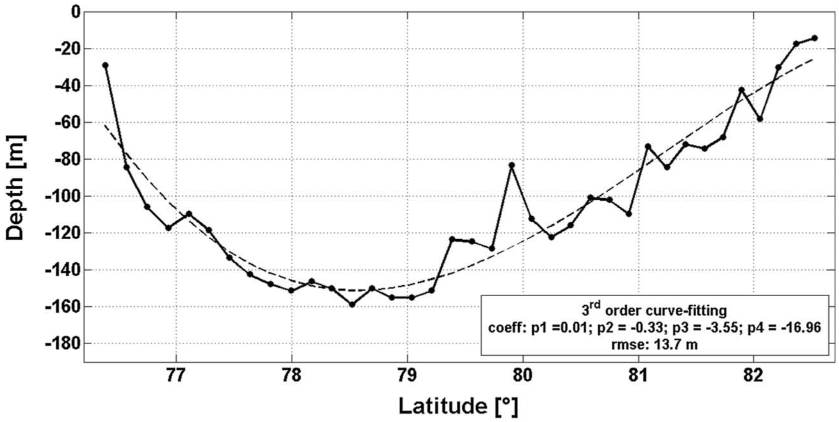

Figure 4. Bathymetric profile across Ligeia Mare. The deepest point of the sea approach to 160 m close to 79° of latitude. The dashed lines indicate the third order polynomial fitting the depths values with an RMS error of about 14 m.

the subsurface echo). This check is performed to ensure the tracking of the first reflection even in the case of multiple scattering centers (i.e., rough subsurface). The recorded two-way travel time was converted into depth obtaining the bathymetry (Figure 4) of Ligeia Mare, assuming the real part of dielectric permittivity of the liquid hydrocarbons be equal to 1.75 [*Wye et al.*, 2009; *Paillou et al.*, 2008], intermediate between pure methane and ethane.

We then estimated the dielectric properties of the liquids by modeling the surface/subsurface radar backscattering properties.

We estimated the loss tangent of the liquid in Ligeia Mare in two ways. First, using a noncoherent Cassini echo model [*Montefredini et al.*, 1995] relating surface /subsurface characteristic to radar echo pulse shape, we isolated a moderate roughness region adequate for data inversion analysis. We assume the sea bottom is essentially uniform in scattering properties for the selected pulses and use the relative variations in subsurface reflection magnitude to derive the corresponding liquid loss tangent. By analyzing the selected radar echoes we estimated the specific radio attenuation of Cassini signal as it propagates through the sea and thus we were able to derive a loss tangent for the assumed hydrocarbon liquids (see section 3 in the supporting information).

A second method for estimating the loss tangent, which does not require the assumption of uniformity, is to compare the magnitudes of the surface and seafloor echoes to that produced by an ideal two-layer scenario, making assumptions regarding the dielectric constant and scattering properties of the surface and subsurface interfaces. By considering flat near-specular surfaces for both interfaces we can obtain an upper bound for the liquid loss tangent, as any seafloor roughness leading to scatter in the nonnadir direction reduces the signal level further. Using this method we find an upper bound on the loss tangent equal to $8 \cdot 10^{-5}$ (see section 4 in the supporting information).

3. Results

The greatest depth we found is of about 160 m, with a seabed slope that is gentler toward the northern shore. The latter is consistent with previously imaged shoreline morphologies suggestive of shallow slopes and sedimentation, very different from the south where steep hills and flooded valleys are found.

The measured depths of Ligeia reconstruct the shape of the seafloor. Assuming the seafloor topography of Ligeia approximated by the curve in Figure 4 we found an root-mean-square (RMS) variation of the depths measurement of 14 m. At 79.5° latitude the radar registered an abrupt variation of the bathymetry of about +50 m where a change of topography, limited along-track within 10 km azimuth resolution, can occur. Excluding this measurement, the RMS errors of the depths are up to 11 m.

Varying the permittivity between the values of pure methane and pure ethane changes the maximum depth by only ±8 m. The most accurate bathymetry measurements are from the northern portion of the sea where we selected data especially suited for radar measurements of loss tangent and where the superresolution method still shows single narrow peaks, see Figures 2a and 2b. The signal attenuation through the sea implies a loss tangent of $(3 \pm 1)*10^{-5}$ and demonstrates that the liquid is remarkably transparent.

These observations and analysis constrain the bulk ethane-methane composition of the liquid more directly than previous observations.

4. Discussion

The maximum measured depth of about 160 m may of course not be the deepest point in Ligeia Mare, but the bathymetry track runs close to the part of Ligeia that is most distant from the shore. Given the overall shallow subsea slopes we measure, we speculate that the maximum depth of liquid does not significantly exceed this value. Such a central depth is somewhat shallower than the ~350 m that has been estimated using the rule of thumb that large lake basins on Earth have a depth/width ratio of ~0.001 [*Lorenz et al.*, 2008]; however, the uncertainties on that estimate allow values a factor of several higher and lower than this.

Assuming that Ligeia depth is greatest at its plan-view centroid and radially decreases as it approaches its shoreline (along quadratic profiles), the observed bathymetry track can be used to extrapolate a total liquid volume of ~10^4 km^3. Given a surface area based on SAR images of 126,000 km^2, this yields an average depth of ~70 m. This in turn corresponds to $5 \cdot 10^{15}$ kg, or 5000 gigatons (GT) of carbon, about 100 times the known terrestrial oil and gas reserves [*Lorenz et al.*, 2008], but still only a small fraction (~1.4%) of the amount of methane vapor in Titan's atmosphere. It is an even smaller fraction of the equivalent (as ethane and methane) amount of methane thought to have been destroyed by photolysis in Titan's atmosphere over the age of the solar system. The depth detection allowed a tight estimate of the amount of liquid hydrocarbon for Ligeia Mare, and paves the way for similar experiments to be conducted by Cassini on the largest Titan sea, Kraken Mare.

The low loss tangent estimate, when combined with the environmental conditions on Titan, essentially rules out any material other than liquid methane-ethane, although introducing nitrogen at the 5–15% level would not appreciably affect the loss tangent estimate. It is near the lowest laboratory estimates for simple liquid alkanes [*Dagg and Reesor*, 1972; *Senn et al.*, 1992; *Gelsthorpe et al.* 1978], and requires that microwave absorbing hydrocarbons, nitriles, and suspended particles be limited to less than the order of 0.1% of the liquid volume. Quantifying the maximum allowable abundances of other expected minor species such as propane, based on the observed transparency of Ligeia, will require new laboratory measurements of their complex dielectric properties.

The dramatic hemispherical distinction between Titan's northern lakes and seas and the handful of liquid-filled depressions in the south, dominated by the apparently shallower Ontario Lacus, has been attributed to the seasonal asymmetry of the present-day climate, where southern summer insolation is more intense but shorter than summer in the north [*Aharonson et al.*, 2009]. This results in prolonged accumulation of methane and ethane in the north [*Schneider et al.*, 2012] and progressive desiccation of the south over timescales of tens of thousands of years. Our observation of a very low loss tangent in Ligeia Mare is in striking contrast to the much stronger absorption estimated at Ontario Lacus (loss tangent ~10^{-3}) [*Hayes et al.*, 2010], where we could nonetheless detect the lake bed through several meters of liquid ethane or ethane-methane [*Brown et al.*, 2008] and possible suspended sediment and/or microwave absorbing solutes [*Clark et al.*, 2010]. Much like the increasing saltiness of terrestrial bodies like the Aral Sea, a desiccating Ontario would become more enriched in less volatile, but more absorbing, compounds such as longer-chain aliphatic hydrocarbons, aromatics, and nitriles, whereas Ligeia has apparently been distilled into exceptional clarity.

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